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Weed Control for Tall Fescue Seed Production and Stand Duration without Burning

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ABSTRACT

Effective weed control was a major concern of Oregon grass seed growers during their recent transition from open-field burning to mechanical methods of managing post-harvest residues. This 4-yr herbicide by residue management study was conducted to determine: (i) efficacy of herbicides on volunteer tall fescue (*Festuca arundinacea* Schreb.) seedlings and other weeds, (ii) whether treatments required for weed-free seed production could be reapplied annually without damaging stands, (iii) occurrence of interactions between herbicides and crop residue management, and (iv) increases in grassy weeds over time. Nearly all herbicide treatments controlled volunteer tall fescue seedlings with bale/flail chop/rake residue removal. Vacuum sweep residue removal improved control over bale/flail chop/rake in many cases, and controlled seedlings even without herbicides in 1995. Incorporation of pendimethalin [*N*-(1-ethylpropyl)-3,4-dimethyl2,6-dinitrobenzenamine] improved weed control in bale/flail chop/rake and residue-retained conditions. Although carryover treatment effects reduced weed seedling survival in later years of production and sometimes reduced tall fescue seed yield, specific treatments existed which controlled weeds for all 4 yr without reducing yield. Interactions between residue management and herbicide treatments included reduced efficacy of pendimethalin in residue-retained management, higher yields at equal weed densities in residue-removed conditions, and higher weed densities from equivalent herbicide treatments in residue-retained conditions. Roughstalk bluegrass (*Poa trivialis* L.) increased over time in some treatments and was a major cause for reduced yields in later years of production. Tall fescue seed growers must risk some current-year yield loss from herbicide injury to avoid greater losses in future years from perennial weeds like roughstalk bluegrass.

Grass seed production in western Oregon underwent a mandatory transition between 1990 and 1996 from open-field burning to mechanical methods of removing or otherwise processing post-harvest residues. Early research had shown that many of the yield benefits from field burning were also provided by mechanical removal of post-harvest residues, but achieving adequate weed control was a concern (Young et al., 1984). Some studies revealed the presence of lingering yield benefits from burning, especially in later years of production for perennial ryegrass (*Lolium perenne* L.) and tall fescue (Young et al., 1999). However, yield differences between burn and non-burn residue management were similar in size to those that could be caused by uncontrolled volunteer perennial ryegrass seedlings (Mueller-Warrant et al., 1994b) or by moderate densities of roughstalk bluegrass (Mueller-Warrant and Brewster, 1986), common occurrences in grass seed fields. Seed laws and market expectations define allowable limits for weed seed contamination, but production efficiency concerns related to yield losses in the field and during seed cleaning can set more stringent limits on tolerable weed density.

Desire by western Oregon grass seed producers to minimize costs associated with their transition from burning led to numerous innovations in production practices. Foremost among these was reexamination of the fundamental principle that crop residues must be removed from the field after harvest to promote tiller regrowth necessary for seed production the following year (Chilcote et al., 1980). As an alternative to removal, residues were sometimes flail-chopped into fine mulch spread uniformly over the field to decompose during the fall and winter (Churchill et al., 1995). As equipment and procedures were developed to efficiently chop straw and stubble into mulch rather than remove it, growers and researchers pondered long-term impacts of this practice. They specifically wondered how crop regrowth, soil moisture, weed seed germination, herbicide performance, seed yield, and stand longevity might differ between residue-removed and residue-retained conditions.

Research in perennial ryegrass and tall fescue seed production using pendimethalin, trifluralin [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine], metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide], and oxyfluorfen [2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl)benzene] applied as preemergence (PRE) herbicides under residue-removed conditions determined which of several key factors were of greatest importance for each herbicide (Mueller-Warrant et al., 1994a, 1994b, 1995a, 1995b; Mueller-Warrant, 1999; Mueller-Warrant and Rosato, 2002a, 2002b). PRE timing of application was most critical for pendimethalin and trifluralin. Incorporation by rainfall within 1 wk after application was most critical for metolachlor. Abundant moisture at the soil surface was most critical for oxyfluorfen. Weed control generally improved when PRE herbicide treatments were followed by postemergence (POST) applications of diuron [*N'*-(3,4-dichlorophenyl)-*N*,*N*-dimethylurea], metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one]), terbacil [5-chloro-3-(1,1-dimethylethyl)-6-methyl-2,4(1*H*,3*H*)-pyrimidinedione], and/or oxyfluorfen. While preliminary tests of pendimethalin applied on top of chopped residues were disappointing, the ability of PRE herbicides to control seedling grasses under residue-removed conditions when even small amounts of rain moved them into the weed seed germination zone suggested that efforts to incorporate herbicides through the straw might be beneficial. While diuron had been

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Abbreviations: EP, early-postemergence; INC, incorporated; LF, leaves; LP, late-postemergence; POST, postemergence; PRE, preemergence.

used by grass seed growers to control weeds since the 1960s, metribuzin and oxyfluorfen first became available in the late 1980s, metolachlor in 1994, and pendimethalin not until 1999.

Grower experience in the early 1990s using POST treatments to control seedling grasses in residue-retained conditions included instances of near-total stand loss in some perennial ryegrass and tall fescue seed crops and poor weed control in others. Possible causes for erratic performance (both weed control efficacy and crop tolerance) in residue-retained compared with residue-removed conditions included (i) better retention of moisture from early fall rains at the soil surface underneath chopped mulch, (ii) larger weeds at a normal POST timing because of earlier weed germination underneath a mulch, (iii) decreased herbicide concentrations (or delay in timing of peak concentration) at the soil surface because of physical or chemical "tying up" of herbicides on the straw mulch under limited rainfall conditions, (iv) changes in crop and/or weed rooting patterns, (v) tiller elongation and yellowing of crops covered by loosely packed straw mulch, (vi) better early fall crop regrowth because of greater soil moisture, and (vii) limited choice in herbicides registered for use on grass seed crops. Any of these factors had the potential to shift the balance between tolerance of established crops and sensitivity of seedling weeds to herbicides. Such a shift could be especially problematic for photosystem-II-inhibiting herbicides such as diuron and metribuzin where no true selectivity exists at the site of action between old established crop plants and young volunteer seedlings. Because some of these factors might increase the activity of a given herbicide treatment while others might decrease it, it was difficult to predict how specific treatments would perform under residue-retained conditions. Uncertainties introduced by possible increases in weed densities over time posed additional challenges to our choice of treatment. Other major concerns were ongoing difficulties the grass seed industry was encountering while trying to maintain existing and add new herbicide registrations, particularly for oxyfluorfen, metolachlor, and pendimethalin. Because of these various unknowns, it was necessary to test a fairly wide range of herbicide treatments in hopes of finding some that could consistently control weeds without undue crop damage and might be eventually registered for such use.

The objectives of this research were to: (i) evaluate the efficacy of herbicide treatments on volunteer tall fescue seedlings and other weeds under residue-retained management and under vacuum sweep and bale/flail chop/rake residue-removed management, (ii) determine whether herbicide treatments could be reapplied annually without damaging tall fescue stands, (iii) identify interactions between crop residue management systems and herbicide treatments, (iv) determine whether common weeds such as annual bluegrass (*Poa annua* L.) and roughstalk bluegrass would increase over time, and (v) quantify the effects of volunteer seedling tall fescue, year-old tall fescue plants, and roughstalk bluegrass on tall fescue seed yield.

MATERIALS AND METHODS

Site Description and Grower Practices

Tests were conducted at Shedd, OR, in a commercial seed production field of 'Rebel Jr' tall fescue planted in September 1990 and harvested in July 1991 and July 1992 by the seed grower. The grower used the carbon band planting technique in which a conventionally tilled seedbed was prepared in late summer and seed was planted in 61-cm-wide rows in early fall. During planting, 2.5-cm-wide bands of activated carbon were applied over the rows at 336 kg ha^{-1} carbon in the treated zone. After planting and before crop emergence, 2.7 kg a.i. ha^{-1} diuron was broadcast-applied to the field. Soon after crop emergence, 1.1 kg a.i. ha^{-1} ethofumesate [(±)-2-ethoxy-2,3-dihydro-3,3-dimethyl-5-benzofuranyl methanesulfonate] was broadcast-applied for annual bluegrass control (Lee, 1973, 1981). Soil types were a combination of Dayton silt loam (fine, montmorillonitic, mesic, Typic Albaqualfs) and Amity silt loam (fine-silty, mixed, mesic Argiaquic Xeric Argialbolls). The cooperating grower used standard practices for fertilization (200 kg ha^{-1} N split-applied in early and mid-spring), disease control (three applications of 0.12 kg a.i. ha^{-1} propiconazole [1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl] methyl]-1*H*-1,2,4-triazole] applied from early May through late June), and broadleaf weed control (1.1 kg a.i. ha^{-1} 2,4-D [(2,4-dichlorophenoxy)acetic acid] plus 0.28 kg a.i. ha^{-1} dicamba [3,6-dichloro-2-methoxybenzoic acid]) applied in early spring) during all years of the study. The grower applied 2.7 kg ha^{-1} diuron POST in fall 1991 for control of seedling broadleaf and grassy weeds. The grower harvested in 1991 and 1992 by swathing the crop into windrows at physiological maturity, and then combining it when dry. No weed density or yield measurements were made during the first 2 yr of seed production because no experimental treatments were applied until fall 1992.

Post-Harvest Residue Management

Residue-Removed

Vacuum sweep and bale/flail chop/rake residue removal methods were chosen to represent the two most widely used extremes in residue-removed management, with vacuum sweep providing more thorough removal of straw, stubble, and seed, while bale/flail chop/rake management was more commercially practical. The bulk of the crop residue was removed after harvest in each year by raking into windrows and baling. In the bale/flail chop/rake treatment, stubble left after the first baling was flail chopped to 7-cm height, raked into windrows adjacent to the plots (Needle-Nose rake manufactured by Rear's Mfg., Eugene, OR), and then removed by baling. In the vacuum sweep treatment, stubble was cut to 3-cm height with a flail head and blown into an enclosed wagon for removal. Residue-removed management treatments were arranged as main plots in a split-plot randomized complete block design with four replicates, with herbicide treatment as the subplot factor. Each residue-removed main plot block was 32.9 by 12.2 m, with 4.6-m-wide alleys between blocks.

Residue-Retained

Post-harvest crop residues in the residue-retained test were spread uniformly over the plots and flail-chopped three times to a 3-cm stubble height. There were two residue-retained main plot treatments, one receiving incorporated (INC) pendimethalin and a second with no PRE herbicide. Each residue-retained main plot block was 21.9 by 12.2 m in size. The majority of subplot herbicide treatments applied in the residue-retained test differed from those applied in the residue-removed test, and so the tests were primarily analyzed as two separate experiments. However, the main blocks in both experiments were randomized together within the first three replicates, allowing for a combined analysis of variance on data for herbicide treatments common to both residue-removed and residue-retained tests.

Herbicide Treatments

Residue-Removed

A total of 12 herbicide treatments, including single-year untreated checks for the first, second, and third growing seasons, were applied as subplots 2.7 m wide by 12.2 m long within residue-removed main plots. Untreated checks were not repeated on the same plots in any two consecutive years because establishment by volunteer crop seedlings and other weeds in 1 yr was known to potentially affect both crop yield and the ability of additional weed seedlings to establish in subsequent years. Herbicides were applied at 243 L ha^{-1} under 207-kPa pressure using a commercial plot sprayer pulled by a 4-wheel all-terrain-vehicle at 4.2 km h^{-1}. The spraying system included bypass agitation that was adjusted by an MT-3000 Sprayer Monitor (Micro-Trak Systems, Inc., Eagle Lake, MN) to maintain constant delivery rate. Management practices and dates are given in Table 1, including herbicide treatments and volunteer tall fescue seedling growth stages when treated. Shallow incorporation of pendimethalin was achieved by use of a rotary rake/tedder within 1 h after herbicide application. Because soil was dry and hard in late summer, tines on the rotary-tedder only scratched 3-mm deep grooves, with most of the dust settling back onto the treated plot. Rainfall was the only source of moisture in all years. Current-year untreated checks received INC pendimethalin followed by POST oxyfluorfen plus diuron during years before or after their untreated year. The 1992–1993 growing season untreated check was reused as the untreated check in the 1995–1996 growing season after having received INC pendimethalin followed by POST oxyfluorfen plus diuron during the two intervening years. Results from all plots receiving INC pendimethalin at 2.2 kg a.i. ha^{-1} followed by POST oxyfluorfen plus diuron the first year were averaged.

Residue-Retained

PRE herbicide treatments were arranged as main plots in a split-plot randomized complete block design with three replicates. The two main plot treatments consisted of application of INC pendimethalin at 2.2 kg ha^{-1} or no PRE application (Table 1). Each PRE herbicide treatment block was 21.9 by 12.2 m in size, with 4.6-m-wide alleys between blocks. Procedures to chop and spread crop residues and to incorporate herbicides evolved rapidly during the course of these tests, and improvements were adopted to match the best practices available to seed growers (J. Rear Sr., personal communication, 1994). Incorporation technique used in the first 2 yr was to apply a granular formulation of pendimethalin on top of the chopped straw, and then rake it into and partly through the straw using a rotary rake/tedder. In the third and fourth years, pendimethalin was sprayed beneath the straw through a boom mounted below a fixed plate behind the rotating knives on a straight-bladed flail chopper. Pendimethalin was applied during what was the final flail chopping of the plots. This application technique allowed the less expensive emulsifiable concentrate formulation to be substituted for the more expensive granular formulation, but equipment to conduct it was not available until 1994.

Seven unique POST herbicide treatment sequences (including a no-POST check) were applied as subplots 2.7 m wide by 12.2 m long within the residue-retained main plots (Table 1). One of these treatment sequences was duplicated and applied to plots that would become the no-POST treatment check in the next growing season or had been the no-POST treatment check in the previous growing season. Results from duplicate treatments in the first year were averaged. POST treatment sequences consisted of sequential early-postemergence (EP) followed by late-postemergence (LP) herbicide applications or a single POST application. LP applications were delayed until crops had visibly recovered from injury caused by EP treatments.

Harvest Techniques

Residue-Removed

From 1993 through 1996, plots were swathed with a modified commercial swather with a 1.5-m-wide head and combined with a small plot combine equipped with windrow pickup attachment. A 1.5-m-wide section through the center of each plot was swathed into windrows for seed yield. Seed was bagged and later cleaned to >99% mechanical purity with an air-screen seed cleaner. Post-harvest residue in each main plot was raked into windrows, baled and weighed to determine straw yield on a main-plot basis. Harvest index was determined by dividing the clean seed yield by the sum of the precleaning seed yield and the straw yield.

Residue-Retained

Harvest techniques were the same as those used in the residue-removed experiment except for the following differences in handling of post-harvest residues. Post-harvest residues in each main plot were raked into windrows, baled, and weighed to determine straw yield on a main-plot basis. After baling and weighing, straw was returned to the same main plots, spread uniformly, and flail-chopped three times to a 3-cm stubble height. Straw was usually returned to plots and chopped within 2 d after raking and baling to minimize differences between our techniques and those of commercial growers whose straw would never be baled in a residue-retained system.

Measurement of Weed Ground Cover

In all years, weed ground cover between rows was determined by examining 500 separate 2.5- by 2.5-cm locations per subplot in late winter for presence of any volunteer tall fescue seedlings at each location. A 6.2-cm^2 area was chosen as the sampling point in ground cover measurements because individual 5-mo-old seedlings were large enough to fully occupy such a space. A metal grid defined a fixed pattern of 50 positions, and the grid itself was dropped at 10 random locations between the originally planted rows within each subplot. The grid was dropped one time in each 10% of the plot length, which generally offered two interrow spaces within which it could land. The fixed pattern of 50 positions within the grid sampled 1.4% of the total area covered by the grid. In the second, third, and fourth years of the study, ground cover of year-old tall fescue plants was also measured. Techniques used to measure ground cover by annual bluegrass and roughstalk bluegrass were similar to those for volunteer tall fescue, except for a 7.2-fold increase in sampling intensity.

Statistical Analyses

Residue-Removed

Data were initially analyzed by means of a split-split-plot design with test years as main plots, vacuum sweep vs. bale/

Table 1. Residue management and herbicide treatments, swathing, combining, and data collection dates for residue-retained and residue-removed experiments, 1993–1996 harvest years.

Main plot treatment	Subplot treatments (kg a.i. ha^{-1})	Treatment date during each 1 Aug.–30 July growing season (seedling growth stage)†			
		1992–1993	1993–1994	1994–1995	1995–1996
Residue-removed experiment	Preemergence (PRE)/postemergence (POST) herbicide treatments				
Vacuum sweep residue removal		16 Aug. 1992	6 Aug. 1993	27 July 1994	11 Aug. 1995
Bale/flail chop/rake residue removal		13–16 Aug. 1992	26 July–4 Aug. 1993	20–22 July 1994	19 July–10 Aug. 1995
	Pendimethalin 2.2 PRE/no POST	8 Oct. 1992/–	21 Oct. 1993 (0–1 LF)/–	21 Oct. 1994/–	29 Sept. 1995/–
	Pendimethalin 2.2 INC/no POST	22 Sept. 1992/–	4 Oct. 1993/–	6 Oct. 1994/–	29 Sept. 1995/–
	Pendimethalin 2.2 PRE/Oxyfluorfen 0.14 + diuron 1.8 POST	8 Oct. 1992/ 24 Nov. (3 LF)	21 Oct. 1993 (0–1 LF)/ 24 Nov. (2 LF)	21 Oct. 1994/ 9 Dec. (2–3 LF)	29 Sept. 1995/ 6 Nov. (2 LF)
	Pendimethalin 1.1 INC/Oxyfluorfen 0.14 + diuron 1.8 POST	22 Sept. 1992/ 24 Nov. (3 LF)	4 Oct. 1993/ 24 Nov. (2 LF)	6 Oct. 1994/ 9 Dec. (2–3 LF)	29 Sept. 1995/ 6 Nov. (2 LF)
	Pendimethalin 2.2 INC/Oxyfluorfen 0.14 diuron 1.8 POST‡	22 Sept. 1992/ 24 Nov. (3 LF)	4 Oct. 1993/ 24 Nov. (2 LF)	6 Oct. 1994/ 9 Dec. (2–3 LF)	29 Sept. 1995/ 6 Nov. (2 LF)
	Metolachlor 2.2 PRE/Oxyfluorfen 0.14 + diuron 1.8 POST	8 Oct. 1992/ 24 Nov. (3 LF)	21 Oct. 1993 (0–1 LF)/ 24 Nov. (2 LF)	21 Oct. 1994/ 9 Dec. (2–3 LF)	29 Sept. 1995/ 6 Nov. (2 LF)
	Oxyfluorfen 0.28 PRE/Oxyfluorfen 0.14 + diuron 1.8 POST	8 Oct. 1992/ 24 Nov. (3 LF)	21 Oct. 1993 (0–1 LF)/ 24 Nov. (2 LF)	21 Oct. 1994/ 9 Dec. (2–3 LF)	29 Sept. 1995/ 6 Nov. (2 LF)
	Pendimethalin 2.2 PRE/Oxyfluorfen 0.14 + metribuzin 0.63 POST	8 Oct. 1992/ 24 Nov. (3 LF)	21 Oct. 1993 (0–1 LF)/ 24 Nov. (2 LF)	21 Oct. 1994/ 9 Dec. (2–3 LF)	29 Sept. 1995/ 6 Nov. (2 LF)
	No PRE/Oxyfluorfen 0.28 + diuron 2.7 POST	–/24 Nov. 1992 (3 LF)	–/24 Nov. 1993 (2 LF)	–/9 Dec. 1994 (2–3 LF)	–/6 Nov. 1995 (2 LF)
	Current-year untreated check	–	–	–	–
	Future-year untreated check	‡	‡	‡	‡
	Past-year untreated check	‡	‡	‡	‡
Seedling ground cover measurement		4 Mar. 1993	21 Mar. 1994	23 Mar. 1995	1 Apr. 1996
Swathing		3 July 1993	30 June 1994	3 July 1995	5 July 1996
Combining		16–30 July 1993	12–15 July 1994	18–19 July 1995	25–30 July 1996
Residue-retained experiment	Early postemergence (EP)/late post-emergence (LP) herbicide treatments				
No PRE (flail chop only)		16 Aug. 1992	2–6 Aug. 1993	26–27 July 1994	9 Aug. 1995
Pendimethalin 2.2 INC		21 Sept. 1992	13 Oct. 1993	29 Sept. 1994	4 Oct. 1995 (1 LF)
	Oxyfluorfen 0.28 + metolachlor 2.2 EP/ Diuron 2.7 LP	28 Oct. 1992 (1 LF)/16 Dec. (4 LF)	8 Nov. 1993 (1 LF)/21 Dec. (3 LF)	14 Nov. 1994 (1 LF)/20 Dec. (3 LF)	6 Nov. 1995 (2 LF)/7 Dec. (4 LF)
	Oxyfluorfen 0.28 + metribuzin 0.63 EP/ Diuron 1.8 LP	28 Oct. 1992 (1 LF)/ 16 Dec. (4 LF)	8 Nov. 1993 (1 LF)/21 Dec. (3 LF)	14 Nov. 1994 (1 LF)/20 Dec. (3 LF)	6 Nov. 1995 (2 LF)/7 Dec. (4 LF)
	Oxyfluorfen 0.28 + terbacil 1.1 EP/ Diuron 1.8 LP¶	28 Oct. 1992 (1 LF)/16 Dec. (4 LF)	8 Nov. 1993 (1 LF)/21 Dec. (3 LF)	14 Nov. 1994 (1 LF)/20 Dec. (3 LF)	6 Nov. 1995 (2 LF)/7 Dec. (4 LF)
	Oxyfluorfen 0.28 EP/Diuron 2.7 LP	28 Oct. 1992 (1 LF)/16 Dec. (4 LF)	8 Nov. 1993 (1 LF)/21 Dec. (3 LF)	14 Nov. 1994 (1 LF)/20 Dec. (3 LF)	6 Nov. 1995 (2 LF)/7 Dec. (4 LF)
	Oxyfluorfen 0.42 + diuron 0.9 EP/ Diuron 1.8 LP	28 Oct. 1992 (1 LF)/16 Dec. (4 LF)	8 Nov. 1993 (1 LF)/21 Dec. (3 LF)	14 Nov. 1994 (1 LF)/20 Dec. (3 LF)	6 Nov. 1995 (2 LF)/7 Dec. (4 LF)
	Current year no-POST check	–	–	–	–
	Past/future year no-POST check	§	¶	¶	¶
	Oxyfluorfen 0.42 + diuron 2.7 POST§	24 Nov. 1992 (3 LF)	21 Dec. 1993 (3 LF)	9 Dec. 1994 (2–3 LF)	6 Nov. 1995 (2 LF)
Seedling ground cover measurement		4 Mar. 1993	21 Mar. 1994	23 Mar. 1995	1 Apr. 1996
Swathing		5 July 1993	30 June 1994	3 July 1995	5 July 1996
Combining		16–30 July 1993	12–15 July 1994	20–24 July 1995	25–30 July 1996

† Treatment timing was PRE to volunteer tall fescue seedlings except where average growth stage in number of leaves (LF) is shown in parentheses.
‡ Untreated checks in the residue-removed experiment received this herbicide treatment in all years except whichever one they were untreated. Untreated checks in the 1995–1996 growing season were plots that had also been untreated checks in the 1992–1993 growing season.
§,¶ Untreated checks (no POST treatment) in the residue-retained experiment received this herbicide treatment (§) in the 1992–1993 growing season before their use as untreated checks in the 1993–1994 growing season, and received this herbicide treatment (¶) in all other years before or after the one in which they were untreated. Untreated checks in the 1994–1995 growing season were plots that had also been untreated checks in the 1992–1993 growing season, while untreated checks in the 1995–1996 growing season were plots that had also been untreated checks in the 1993–1994 growing season.

flail chop/rake residue removal as subplots, and herbicide treatments as subsubplots. However, Bartlett's chi-square test (Steel et al., 1997) indicated heterogeneity of variances among years for tall fescue seed yield, harvest index, and roughstalk bluegrass ground cover (Table 2). Data for these responses were therefore analyzed separately for each year by a split-plot design. Volunteer tall fescue seedling ground cover and roughstalk bluegrass ground cover were transformed by taking log (1 + % ground cover) in all analyses of variance to correct for nonhomogeneous error variances among treatments (Little and Hills, 1978; Steel et al., 1997). The LSD ($P = 0.05$) was used to perform means separation tests. Means separation tests

Table 2. *F* values from analyses of variance for tall fescue volunteer seedling ground cover, clean seed yield, harvest index, and roughstalk bluegrass ground cover.

Source of variation	Degrees of freedom	*F* values: Volunteer seedling ground cover	Clean seed yield	Harvest index	Roughstalk bluegrass ground cover
		Residue-removed experiment, 1992–1993 growing season			
Vacuum sweep vs. bale/flail chop/rake residue management	1	28.86***	0.25NS	0.03NS	–
Herbicide treatment	11	41.55***	0.71NS	0.70NS	–
Residue management × herbicide treatment	11	1.21NS	1.68†	1.46NS	–
		Residue-removed experiment, 1993–1994 growing season			
Vacuum sweep vs. bale/flail chop/rake residue management	1	183.30***	3.27NS	2.83NS	0.64NS
Herbicide treatment	11	44.56***	4.83***	4.72***	1.39NS
Residue management × herbicide treatment	11	7.66***	1.47NS	1.45NS	0.61NS
		Residue-removed experiment, 1994–1995 growing season			
Vacuum sweep vs. bale/flail chop/rake residue management	1	37.03***	10.76†	0.71NS	2.84NS
Herbicide treatment	11	9.94***	6.60***	7.06***	3.37***
Residue management × herbicide treatment	11	5.80***	0.76NS	0.76NS	3.35***
		Residue-removed experiment, 1995–1996 growing season			
Vacuum sweep vs. bale/flail chop/rake residue management	1	25.45***	67.51**	16.11†	2.72NS
Herbicide treatment	11	32.01***	6.08***	5.97***	6.96***
Residue management × herbicide treatment	11	2.12†	1.35NS	1.40NS	2.26†
		Residue-removed experiment, all growing seasons pooled			
Year	3 (2)‡	56.27***	293.15***	229.14***	5.05*
Vacuum sweep vs. bale/flail chop/rake residue management	1	225.62***	22.86***	8.40†	6.01†
Year × residue management	3 (2)‡	16.34***	4.20†	1.53NS	0.69NS
Herbicide treatment	11	110.07***	4.75***	5.06***	10.09***
Residue management × herbicide treatment	11	6.88***	1.62*	1.50NS*	4.67***
Year × herbicide treatment	33 (22)‡	6.06***	2.62***	2.69***	1.85†
Year × residue management × herbicide treatment	33 (22)‡	3.26***	1.39*	1.29NS	0.79NS
Bartlett's chi-square test for homogeneity of variances	3 (2)‡	3.39NS	36.87***	16.51***	13.08**
		Residue-retained experiment, 1992–1993 growing season			
No PRE vs. pendimethalin INC	1	40.96***	2.58NS	0.02NS	–
POST herbicide treatment	7	17.28***	3.60**	3.57†	–
PRE × POST herbicide treatment	7	0.41NS	2.86†	1.58NS	–
		Residue-retained experiment, 1993–1994 growing season			
No PRE vs. pendimethalin INC	1	135.91***	15.29**	8.05†	1.62NS
POST herbicide treatment	7	16.17***	4.30***	3.57**	0.85NS
PRE × POST herbicide treatment	7	0.95NS	0.55NS	0.33NS	0.97NS
		Residue-retained experiment, 1994–1995 growing season			
No PRE vs. pendimethalin INC	1	2.29NS	8.70†	4.14NS	6.15†
POST herbicide treatment	7	1.59NS	1.89*	1.94*	5.98***
PRE × POST herbicide treatment	7	2.92†	1.71NS	1.78NS	3.94***
		Residue-retained experiment, 1995–1996 growing season			
No PRE vs. pendimethalin INC	1	0.77NS	3.51NS	1.98NS	7.22†
POST herbicide treatment	7	3.23**	2.56†	5.68***	8.33***
PRE × POST herbicide treatment	7	0.94NS	0.54NS	1.33NS	5.82***
		Residue-retained experiment, all growing seasons pooled			
Year	3 (2)‡	4.97†	42.12***	11.69**	1.72NS
No PRE vs. pendimethalin INC	1	124.04***	33.75***	5.87†	11.74†
Year × PRE	3 (2)‡	14.43***	1.19NS	1.12NS	0.51NS
POST herbicide treatment	7	27.64***	5.65***	6.37***	11.16***
PRE × POST herbicide treatment	7	1.84†	1.31NS	1.23NS	7.47***
Year × POST herbicide treatment	21 (14)‡	4.23***	2.18**	2.04**	1.99†
Year × PRE × POST herbicide treatment	21 (14)‡	0.77NS	1.38NS	1.06NS	1.16NS
Bartlett's chi-square test for homogeneity of variances	3 (2)‡	7.54*	5.35NS	46.62***	3.09NS

* Significant *F* tests at the 0.1 probability level.
† Significant *F* tests at the 0.05 probability level.
** Significant *F* tests at the 0.01 probability level.
*** Significant *F* tests at the 0.001 probability level.
NS, nonsignificant at the 0.1 level.
‡ Fewer degrees of freedom because 1993 data were not included in roughstalk bluegrass analysis over years.

Table 3. Ground cover of tall fescue volunteer seedlings among herbicide treatments with residue-removed management from 1993 through 1996.

PRE/POST herbicide treatment (kg a.i. ha^{-1})	Vacuum sweep residue removal 1993	1994	1995	1996	Bale/flail chop/rake residue removal 1993	1994	1995	1996
	% ground cover							
Pendimethalin 2.2 PRE/no POST	6.6d‡	0.5ab	0.2ab	0.6b	7.9d	5.8e	1.9de	3.7e
Pendimethalin 2.2 INC/no POST	4.2cd	0.2a	0.4ab	0.4ab	5.4cd	1.4bc	0.7abc	2.1de
Pendimethalin 2.2 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	2.4bc	0.2a	0.1a	0.2ab	4.0bc	2.8cd	1.0bcd	1.0cd
Pendimethalin 1.1 INC/oxyfluorfen 0.14 + diuron 1.8 POST	2.0b	0.2a	0.1a	0.0ab	4.3c	0.6ab	0.4ab	0.2a
Pendimethalin 2.2 INC/oxyfluorfen 0.14 + diuron 1.8 POST	1.7b	0.0a	0.1a	0.0a	2.1b	0.4a	0.6abc	0.2ab
Metolachlor 2.2 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	0.3a	0.1a	0.1a	0.0a	0.5a	1.3b	0.2a	0.2ab
Oxyfluorfen 0.28 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	1.4b	0.2a	0.1a	0.2ab	5.0cd	5.6e	0.6abc	0.2ab
Pendimethalin 2.2 PRE/oxyfluorfen 0.14 + metribuzin 0.63 POST	1.7b	0.3a	0.1a	0.0a	3.3bc	4.2de	1.2cde	0.6abc
no PRE/oxyfluorfen 0.28 + diuron 2.7 POST	1.4b	0.2a	0.3ab	0.2ab	3.8bc	12.5f	2.3e	1.3cd
Current-year untreated check	22.0e	7.7c	0.7ab	10.3c	45.3e	53.1g	11.7f	10.5f
Future-year untreated check	2.1b	0.0a	0.3ab	0.0ab	4.4c	1.3b	0.6abc	1.1cd
Past-year untreated check	–	1.2b	0.8b	0.1ab	–	5.9e	0.7abc	0.8bc
	Treatment contrasts							
Untreated check	22.0	7.7	0.7	10.3	45.3	53.1	11.7	10.5
11-treatment mean	2.0	0.3	0.2	0.1	3.7	2.8	0.8	0.8
Significance	***	***	*	***	***	***	***	***
No PRE/oxyfluorfen 0.28 + diuron 2.7 POST	1.4	0.2	0.3	0.2	3.8	12.5	2.3	1.3
10-treatment mean	2.1	0.3	0.2	0.1	3.7	2.4	0.7	0.8
Significance	NS	NS	NS	NS	NS	***	***	NS
Past-year untreated check	–	1.2	0.8	0.1	–	5.9	0.7	0.8
9-treatment mean	2.1	0.2	0.2	0.1	3.7	2.1	0.7	0.8
Significance	–	***	***	NS	–	***	NS	NS
Pendimethalin 2.2 PRE (2-treatment mean)	4.1	0.3	0.2	0.4	5.6	4.1	1.4	2.1
Pendimethalin 2.2 INC (2-treatment mean)	2.7	0.1	0.2	0.2	3.5	0.9	0.6	0.9
Significance	*	NS	NS	NS	†	***	†	**
Pendimethalin 2.2 (PRE and INC)/no POST	5.3	0.3	0.3	0.5	6.5	3.0	1.2	2.8
Pendimethalin 2.2 (PRE and INC)/ 4-POST-treatment mean	2.0	0.1	0.2	0.1	3.6	1.9	0.8	0.7
Significance	***	NS	NS	†	***	†	NS	***

* Significant F tests at the 0.1 probability level.
† Significant F tests at the 0.05 probability level.
** Significant F tests at the 0.01 probability level.
*** Significant F tests at the 0.001 probability level.
NS, nonsignificant at the 0.1 level.
‡ Means followed by the same letter do not differ at the $P = 0.05$ level within residue management treatments within years.

on volunteer tall fescue seedling ground cover and roughstalk bluegrass ground cover were conducted on log-transformed data, which were then converted back to linear format and expressed as percentage ground cover. Single degree of freedom planned contrasts were used to characterize several important treatment factors, including current-year untreated vs. all herbicide treatments, POST-only vs. all other herbicide treatment sequences, past-year untreated vs. all herbicide treatments that included a PRE component, pendimethalin PRE vs. INC, and pendimethalin alone vs. pendimethalin followed by POST treatments. Analyses of covariance were conducted to adjust tall fescue seed yield for effects of volunteer seedling tall fescue ground cover, year-old tall fescue ground cover, and roughstalk bluegrass ground cover (Little and Hills, 1978).

Residue-Retained

Data were initially analyzed by a split-split-plot design with test years as main plots, PRE herbicide treatments as subplots, and POST herbicide treatments as subsubplots. Bartlett's chi-square test indicated heterogeneity of variances among years for harvest index but not for the other responses. Data for harvest index were therefore analyzed separately for each year by a split-plot design. Single degree of freedom planned contrasts were used to characterize several important treatment factors, including INC pendimethalin vs. no PRE treatment, current-year POST untreated vs. 7-treatment mean, past-year POST untreated vs. 6-treatment mean, and single-timing POST treatment vs. EP plus LP treatment sequences. All other statistical procedures were similar to those used in analyzing the residue-removed experiment.

RESULTS AND DISCUSSION

Control of Volunteer Tall Fescue

Residue-Removed

Three-way interaction occurred between years, residue removal method, and herbicide treatment for volunteer tall fescue seedling ground cover (Table 2). Without herbicide treatment, volunteer seedling ground cover varied greatly among years and residue removal methods, ranging from a high of 53.1% ground cover in 1994 with bale/flail chop/rake residue removal to a low of 0.7% ground cover in 1995 with vacuum sweep (Table 3). Vacuum sweep reduced volunteer seedling ground cover compared with bale/flail chop/rake residue removal in the first 3 yr but not the fourth. Herbicides generally caused highly significant reductions in volunteer seedling ground cover, but the magnitude of the average

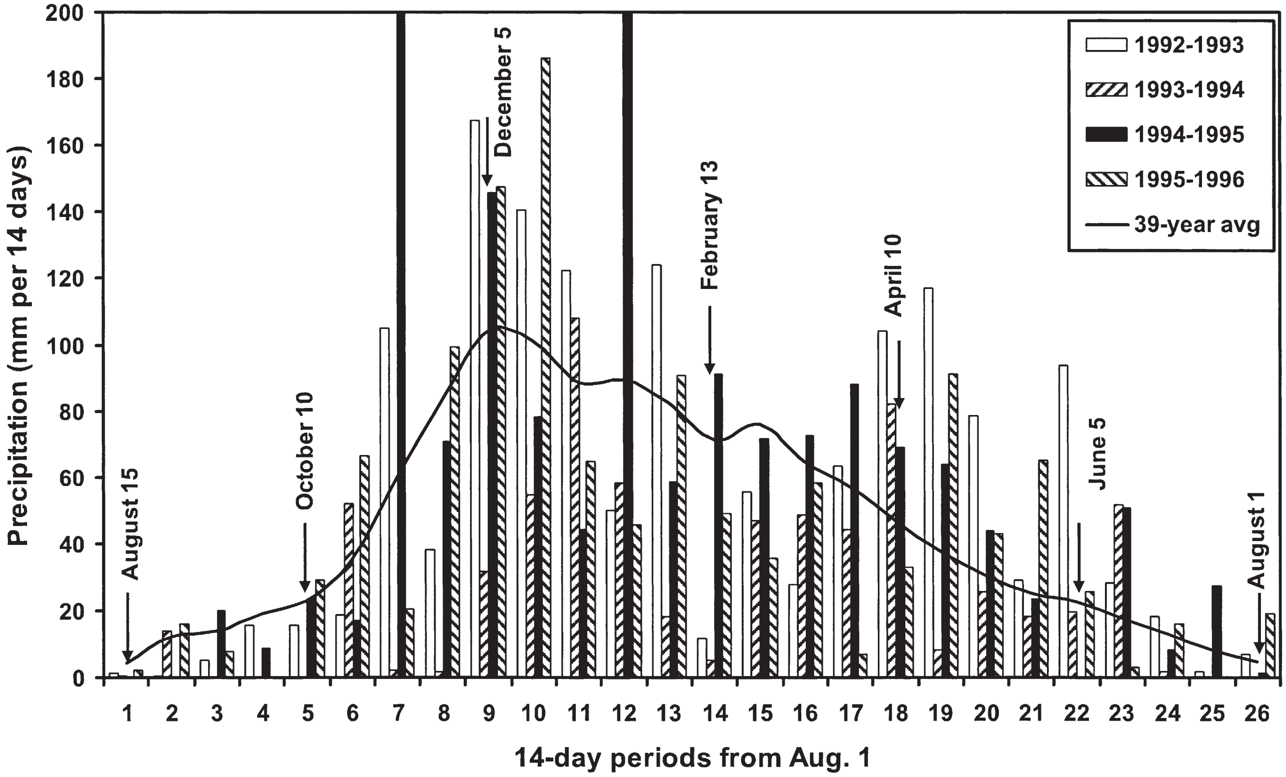

Fig. 1. Precipitation patterns over the 1992–1993, 1993–1994, 1994–1995, and 1995–1996 growing seasons at Shedd, OR.

reduction varied from a low of 2.9-fold in 1995 vacuum sweep to a high of 70-fold in 1996 vacuum sweep. Only six out of 11 herbicide treatments reduced seedling ground cover in 1995 with vacuum sweep residue removal, probably because vacuum sweeping itself was so effective that year.

Rainfall patterns likely caused many of the differences among years (Fig. 1). For example, most of the fall of 1993 was drier than normal, and seedlings that germinated in late August experienced no rainfall during the next 6 wk, while those that germinated in late October experienced no rainfall during the next 4 wk. The much higher seedling ground cover in untreated checks with bale/flail chop/rake than vacuum sweep residue removal in the 1993–1994 growing season likely represented differential seedling survival under moisture-stress conditions in addition to physical removal of seeds by vacuum sweeping. Another possible cause for differences among years could be an accumulation of herbicide residues within plots that received the same treatments annually from the fall of 1992 through the fall of 1995. While soils were not tested for herbicide residues in this test, carryover of high levels of diuron has been found to occur in grass seed fields (C. Mallory-Smith, unpublished data, 1995–1996). Another possible reason for declining volunteer seedling ground cover over time was a reduction in open space available for seedling establishment caused by increases in ground cover of roughstalk bluegrass and year-old tall fescue.

POST-only oxyfluorfen plus diuron did not differ in effectiveness from the other 10 treatments with vacuum sweep in any year and with bale/flail chop/rake residue removal the first and fourth years (Table 3). In the second and third years with bale/flail chop/rake residue removal, however, treatments that included PRE herbicides had three to five times lower volunteer seedling ground cover than the POST-only treatment. Incorporation of pendimethalin reduced volunteer seedling ground cover in all years with bale/flail chop/rake residue removal, and in the first year with vacuum sweep. In the last 3 yr with vacuum sweep, both PRE and INC pendimethalin were highly effective. Following-up PRE or INC pendimethalin with POST herbicide treatments improved control two out of 4 yr with vacuum sweep and three out of 4 yr with bale/flail chop/rake residue removal. The higher rate of INC pendimethalin (2.2 vs. 1.1 kg ha^{-1}) improved control in only one case, bale/flail chop/rake residue removal the first year. Volunteer tall fescue seedling density in the past-year untreated check was higher than for the nine-herbicide-treatment mean the second year with both residue removal methods and the third year with vacuum sweep.

Residue-Retained

Year × PRE and year × POST treatment interactions occurred for volunteer tall fescue seedling ground cover, but PRE × POST treatment interaction was significant only in the third year (Table 2). Similar to results in the residue-removed test, volunteer tall fescue seedling ground cover declined over time (Table 4). Without any PRE or POST herbicide treatment, volunteer seedling ground cover was 69.7, 36.0, 15.8, and 6.6% in 1993, 1994, 1995, and 1996, respectively (3-way interaction level

Table 4. Ground cover of tall fescue volunteer seedlings among herbicide treatments with residue-retained management from 1993 through 1996.

Main effects	1993	1994	1995	1996
	% ground cover			
PRE herbicide treatment (kg a.i. ha^{-1})				
No PRE herbicide	14.6b†	9.2b	6.4a	3.0a
Pendimethalin 2.2 INC	3.2a	1.1a	4.6a	2.4a
POST herbicide treatment (kg a.i. ha^{-1})				
Oxyfluorfen 0.28 + metolachlor 2.2 EP/diuron 2.7 LP	2.0a	2.0a	2.9a	1.0a
Oxyfluorfen 0.28 + metribuzin 0.63 EP/diuron 1.8 LP	10.0b	3.1ab	5.9ab	4.0c
Oxyfluorfen 0.28 + terbacil 1.1 EP/diuron 1.8 LP	2.4a	2.2a	5.2ab	4.4c
Oxyfluorfen 0.28 EP/diuron 2.7 LP	6.7b	4.3b	4.9ab	2.5abc
Oxyfluorfen 0.42 + diuron 0.9 EP/diuron 1.8 LP	–	3.0ab	5.6ab	1.5ab
Current year no-POST check	37.9c	17.0c	6.7b	4.5c
Past year no-POST check	–	3.1ab	8.6b	3.1bc
Oxyfluorfen 0.42 + diuron 2.7 POST	7.4b	2.3a	5.1ab	2.1abc
	Treatment contrasts			
Current year no-POST treatment	37.9	17.0	6.7	4.5
7-POST mean	5.3	2.8	5.3	2.5
Significance	***	***	NS	‡
Past year no-POST treatment	–	3.1	8.6	3.1
6-POST mean	4.8	2.7	4.8	2.4
Significance	–	NS	‡	NS
Oxyfluorfen 0.42 + diuron 2.7 POST	7.4	2.3	5.1	2.1
EP + LP 5-herbicide mean	4.4	2.8	4.8	2.4
Significance	‡	NS	NS	NS

*** Significant *F* tests at the 0.001 probability level.
NS, nonsignificant at the 0.1 level.
† Means followed by the same letter do not differ at the $P = 0.05$ level within PRE herbicide main plot or POST herbicide subplot treatments.
‡ Significant *F* tests at the 0.1 probability level.

data not shown in Table 4). Averaged over all POST treatments, application of INC pendimethalin reduced volunteer seedling ground cover by 4.6-fold in 1993 and 8.4-fold in 1994. In the last 2 yr, effects of pendimethalin were significant only in the absence of POST treatment, reducing volunteer seedling ground cover by 6.1-fold in 1995 and 2.3-fold in 1996 (3-way interaction level data not shown in Table 4). A likely reason for reduced effectiveness of pendimethalin in the final year was the application timing. Volunteer seedlings were in a 1-leaf growth stage when INC pendimethalin was applied on 4 Oct. 1995, unlike the three previous years when applications were truly PRE in timing (Table 1). The similarity in performance of INC pendimethalin in the first 3 yr suggests that the new application technique first employed in the 1994–1995 growing season, spraying beneath the straw while flail chopping, worked about as well as the older technique of applying a granular formulation and raking it through the straw. However, the two application techniques were never directly compared.

POST herbicide treatments reduced volunteer seedling ground cover in all years except 1995, when they reduced ground cover only in plots not treated with PRE pendimethalin (3-way interaction level data not shown in Table 4). The magnitude of the reduction in ground cover was greater in the first 2 yr than in the last 2 yr. There was no carry-over effect from the past-year no-POST-treatment check except in 1995 when seedlings were more easily controlled in plots that had received POST treatments the previous year. The single-application POST treatment controlled volunteer tall fescue seedlings equally well as the various EP followed by LP treatment combinations in all years except the first. Many of these results are consistent with year-to-year carryover of herbicide residues at levels sufficient to either kill seedlings directly or increase their susceptibility to treatments applied in the later years of the study.

Seed Yield and Harvest Index

Residue-Removed

Interactions between residue removal method and herbicide treatment for seed yield and harvest index were nonsignificant in all years except the first, when the interaction was marginally ($P = 0.1$) significant for seed yield (Table 2). Main effects of residue removal method were nonsignificant the first 2 yr for seed yield, and the first 3 yr for harvest index. Where differences did exist between residue removal methods, vacuum sweep yielded more than bale/flail chop/rake (Table 5). Because yield differences increased over time, possible causes that should be considered include weeds whose prevalence also increased over time, specifically roughstalk bluegrass and year-old volunteer tall fescue.

There were no significant herbicide treatment effects on yield or harvest index the first year of the experiment (Table 5). In the second year, all treatment contrasts were nonsignificant except for a 266 kg ha^{-1} yield loss for the past-year untreated check compared with the average of the nine treatments that included a PRE herbicide component. This yield loss was clearly caused by weeds that established in the first year of the experiment, and underscores one of the major reasons farmers apply herbicides to their grass seed crops. The third year of the experiment there was a 157 kg ha^{-1} yield advantage for the current-year untreated check compared with the average of all herbicide treatments. There was also a 138 kg ha^{-1} yield loss in the past-year untreated check compared with the average of the nine treatments that included a PRE herbicide component. There was an aver-

Table 5. Tall fescue clean seed yield and harvest index among residue-removed management and herbicide treatments from 1993 through 1996.

Main effects	Clean seed yield				Harvest index			
	1993	1994	1995	1996	1993	1994	1995	1996
	seed yield, kg ha^{-1}				seed yield as % of total harvested dry matter			
Residue management treatments								
Vacuum sweep	2065a†	1248a	1082a	1022a	20.3a	12.9a	9.9a	9.8a
Bale/flail chop/rake	2086a	1133a	934b	824b	20.4a	11.1a	9.0a	7.5b
PRE/POST herbicide treatment (kg a.i. ha^{-1})								
Pendimethalin 2.2 PRE/no POST	2105a	1168b	1105ab	800ef	20.6a	11.8b	10.3ab	7.6ef
Pendimethalin 2.2 INC/no POST	1998a	1247ab	1144a	1066a	19.8a	12.5ab	10.5a	9.7a
Pendimethalin 2.2 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	2078a	1188b	1053abc	1006ab	20.3a	12.0b	9.9abc	9.3ab
Pendimethalin 1.1 INC/oxyfluorfen 0.14 + diuron 1.8 POST	2065a	1193b	995bc	991abc	20.3a	12.0b	9.4bc	9.1abc
Pendimethalin 2.2 INC/oxyfluorfen 0.14 + diuron 1.8 POST	2130a	1185b	1051abc	992abc	20.8a	11.9b	9.8abc	9.2abc
Metolachlor 2.2 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	2180a	1334a	977cd	982abc	21.3a	13.2a	9.2cd	9.1abc
Oxyfluorfen 0.28 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	2079a	1194b	871de	895cde	20.5a	12.1b	8.3de	8.4cde
Pendimethalin 2.2 PRE/oxyfluorfen 0.14 + metribuzin 0.63 POST	2128a	1219b	1077abc	908bcd	20.7a	12.3ab	10.0abc	8.5bcd
No PRE/oxyfluorfen 0.28 + diuron 2.7 POST	2013a	1204b	985bcd	901b-e	19.8a	12.1b	9.3bcd	8.5b-e
Current-year untreated check	2035a	1219b	1152a	821def	20.1a	12.3ab	10.6a	7.8def
Future-year untreated check	2047a	1184b	820e	758f	20.1a	12.0b	7.9e	7.2f
Past-year untreated check	–	947c	872de	954bc	–	9.9c	8.3de	8.9abc
			Treatment contrasts					
Untreated check	2035	1219	1152	821	20.1	12.3	10.6	7.8
11-treatment mean	2079	1188	995	932	20.4	12.0	9.4	8.7
Significance	NS	NS	***	**	NS	NS	***	**
No PRE/oxyfluorfen 0.28 + diuron 2.7 POST	2013	1204	985	901	19.8	12.1	9.3	8.5
10-treatment mean	2086	1186	996	935	20.5	12.0	9.4	8.7
Significance	NS	NS	NS	NS	NS	NS	NS	NS
Past-year untreated check	–	947	872	954	–	9.9	8.3	8.9
9-treatment mean	2086	1213	1010	933	20.5	12.2	9.5	8.7
Significance	–	***	**	NS	–	***	**	NS
Pendimethalin 2.2 PRE (2-treatment mean)	2091	1178	1079	903	20.4	11.9	10.1	8.5
Pendimethalin 2.2 INC (2-treatment mean)	2064	1216	1097	1029	20.3	12.2	10.2	9.5
Significance	NS	NS	NS	**	NS	NS	NS	**
Pendimethalin 2.2 (PRE and INC)/no POST	2051	1207	1125	933	20.2	12.2	10.4	8.7
Pendimethalin 2.2 (PRE and INC)/ 4-POST-treatment mean	2086	1194	1000	916	20.4	12.0	9.4	8.6
Significance	NS	NS	***	NS	NS	NS	***	NS

** Significant F tests at the 0.01 probability level.
*** Significant F tests at the 0.001 probability level.
NS, nonsignificant at the 0.1 level.
† Means followed by the same letter do not differ at the $P = 0.05$ level within residue management main plot or herbicide application subplot treatments.

age 125 kg ha^{-1} yield loss when POST treatments were applied after PRE or INC pendimethalin. Because these particular POST treatments could only have improved weed control, yield loss associated with their use must be a direct result of crop injury by the treatments. In the fourth year, there was a 111 kg ha^{-1} yield loss for the current-year untreated check compared with the average of all herbicide treatments. There was also a 126 kg ha^{-1} yield advantage for INC pendimethalin compared with PRE pendimethalin. Herbicide treatment contrasts for harvest index followed the same patterns as those for seed yield.

The simultaneous evidence for beneficial and detrimental effects of herbicides highlights a general predicament of grass seed growers: crop yields can be hurt by weeds that are not controlled, by herbicides applied in attempts to control weeds, and sometimes by both factors simultaneously. The growers' dilemma over how aggressively to try to kill their weeds is further compounded by the cost of seed cleaning to remove weed seeds, the opportunistic nature of weeds like annual bluegrass that proliferate into space made available by injury or death of crop plants, the increase over time of established perennial weeds, and the gradual buildup over years of herbicide residues in the soil profile.

Residue-Retained

Interactions between PRE and POST herbicide treatments for seed yield and harvest index were nonsignificant in all years except the first, when an interaction occurred for seed yield (Table 2). This interaction consisted of an average 282 kg ha^{-1} yield advantage for INC pendimethalin for three of the POST treatments: EP oxyfluorfen plus metolachlor followed by LP diuron, EP oxyfluorfen plus metribuzin followed by LP diuron, and EP oxyfluorfen followed by LP diuron (interaction level data not show in Table 6). For all other POST treatments the first year, there was an average yield loss of 54 kg ha^{-1} when INC pendimethalin was applied. In

Table 6. Tall fescue clean seed yield and harvest index among herbicide treatments with residue-retained management from 1993 through 1996.

Main effects	Clean seed yield 1993	1994	1995	1996	Harvest index 1993	1994	1995	1996
	seed yield, kg ha^{-1}				seed yield as % of total harvested dry matter			
PRE herbicide treatment (kg a.i. ha^{-1})								
No PRE herbicide	1750a‡	866b	808b	609a	12.1a	7.9b	6.6a	5.7a
Pendimethalin 2.2 INC	1840a	1033a	962a	707a*	12.5a	9.4a	8.2a	6.3a
POST herbicide treatment (kg a.i. ha^{-1})								
Oxyfluorfen 0.28 + metolachlor 2.2 EP/diuron 2.7 LP	1731bc	1041ab	1049a	824a	11.9a	9.4ab	8.6a	7.4a
Oxyfluorfen 0.28 + metribuzin 0.63 EP/diuron 1.8 LP	1696c	1001abc	832b	686ab	11.7a	9.1ab	7.1b	6.3b
Oxyfluorfen 0.28 + terbacil 1.1 EP/diuron 1.8 LP	1860ab	925cd	920ab	644bc	12.7a	8.5bc	7.7ab	5.9b
Oxyfluorfen 0.28 EP/diuron 2.7 LP	1892a	952bcd	901ab	623bc	12.9a	8.7abc	7.6ab	5.7b
Oxyfluorfen 0.42 + diuron 0.9 EP/diuron 1.8 LP	–	871de	818b	637bc	–	7.7cd	6.9b	5.8b
Current-year no-POST check	1642c	1070a	863b	695ab	11.4a	9.6a	7.3b	6.2b
Past-year no-POST check	–	762e	801b	493c	–	7.1d	6.8b	4.5c
Oxyfluorfen 0.42 + diuron 2.7 POST	1873ab	975a–d	895ab	664b	12.8a	8.9ab	7.5ab	6.1b
Treatment contrasts								
Current year no-POST treatment	1642	1070	863	695	11.4	9.6	7.3	6.2
7-POST mean	1821	932	888	653	12.5	8.5	7.5	6.0
Significance	***	***	NS	NS	†	**	NS	NS
Past year no-POST treatment	–	762	801	493	–	7.1	6.8	4.5
6-POST mean	1823	961	902	680	12.5	8.7	7.6	6.2
Significance	–	***	*	**	–	***	NS	***
Oxyfluorfen 0.42 + diuron 2.7 POST	1873	975	895	664	12.8	8.9	7.5	6.1
EP + LP 5-herbicide mean	1795	958	904	683	12.3	8.7	7.6	6.2
Significance	NS	NS	NS	NS	NS	NS	NS	NS

* Significant *F* tests at the 0.1 probability level.
† Significant *F* tests at the 0.05 probability level.
** Significant *F* tests at the 0.01 probability level.
*** Significant *F* tests at the 0.001 probability level.
NS, nonsignificant at the 0.1 level.
‡ Means followed by the same letter do not differ at the $P = 0.05$ level within PRE herbicide main plot or POST herbicide subplot treatments.

the second and third years, the yield advantage for INC pendimethalin averaged 167 and 154 kg ha^{-1}, respectively (Table 6). In the fourth year, the average yield advantage for pendimethalin dropped to a nonsignificant 98 kg ha^{-1}. However, yield advantage for pendimethalin still existed in past- and current-year no-POST checks, averaging 230 kg ha^{-1} more seed (interaction level data not shown in Table 6).

The current-year no-POST treatment check yielded 179 kg ha^{-1} less seed the first year than average for all the other POST treatments (Table 6). In the second year, the current-year no-POST treatment check yielded 128 kg ha^{-1} more seed than the seven other treatments, while the past-year no-POST check yielded 199 kg ha^{-1} less seed than the six remaining POST treatments. In the third and fourth years, the current-year no-POST checks did not differ from the average for the seven other treatments. The past-year no-POST treatment checks continued to perform poorly, averaging 101 and 187 kg ha^{-1} less seed than the six remaining POST treatments. Similar to results in the residue-removed experiment, seed yield in residue-retained conditions simultaneously displayed the effects of competition from uncontrolled weeds and crop injury from some of the herbicides. The various POST treatments were associated with yield losses more often than INC pendimethalin was.

Roughstalk Bluegrass Proliferation

Residue-Removed

Roughstalk bluegrass seedlings were few in number, widely scattered, and difficult to identify during the first year, and no reliable data on their abundance were collected. With vacuum sweep residue removal, roughstalk bluegrass ground cover remained very low in the second and third years, and none of the herbicide treatment contrasts were significant (Table 7). In the fourth year, roughstalk bluegrass ground cover with vacuum sweep residue removal in the current-year untreated check was 17-fold greater than the average of all other herbicide treatments. Interaction occurred between residue removal method and herbicide treatment for roughstalk bluegrass ground cover in the last 2 yr of the study (Table 2). Roughstalk bluegrass ground cover was much higher in bale/flail chop/rake residue removal than in vacuum sweep, and many more differences among herbicide treatments were detected. With bale/flail chop/rake residue removal, roughstalk bluegrass ground cover in the current-year untreated check was 8-, 13-, and 15-fold greater than the average of all other herbicide treatments in 1994, 1995, and 1996, respectively (Table 7). Roughstalk bluegrass ground cover was also significantly higher in the past-year untreated check than for the nine-treatment mean in 1994 and 1996. Roughstalk bluegrass ground cover in 1995 was higher in the POST-only treatment than for the 10-treatment mean. Incorporating pendimethalin improved control of roughstalk bluegrass in 1996, as did following-up pendimethalin with POST treatments.

Low numbers and erratic distribution of roughstalk bluegrass limited our ability to detect herbicide treatment effects in 1994 and 1995 with vacuum sweep residue removal (Table 7). With vacuum sweep in 1996, all herbicide treatments reduced roughstalk bluegrass ground

Table 7. Ground cover of roughstalk bluegrass among herbicide treatments with residue-removed management from 1994 through 1996.

	Vacuum sweep			Bale/flail chop/rake		
	1994	1995	1996	1994	1995	1996
	% ground cover					
PRE/POST herbicide treatment (kg a.i. ha^{-1})						
Pendimethalin 2.2 PRE/no POST	0.00a‡	0.00a	0.30ab	0.28abc	0.54ab	3.00c
Pendimethalin 2.2 INC/no POST	0.11a	0.00a	0.00a	0.01a	0.04a	0.67ab
Pendimethalin 2.2 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	0.00a	0.00a	0.00a	0.01a	0.10a	0.06a
Pendimethalin 1.1 INC/oxyfluorfen 0.14 + diuron 1.8 POST	0.00a	0.00a	0.12a	0.00a	0.00a	0.00a
Pendimethalin 2.2 INC/oxyfluorfen 0.14 + diuron 1.8 POST	0.05a	0.00a	0.00a	0.00a	0.10a	0.16a
Metolachlor 2.2 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	0.00a	0.00a	0.28ab	0.24abc	0.12a	0.35a
Oxyfluorfen 0.28 PRE/oxyfluorfen 0.14 + diuron 1.8 POST	0.00a	0.00a	0.00a	0.03a	0.22ab	0.16a
Pendimethalin 2.2 PRE/oxyfluorfen 0.14 + metribuzin 0.63 POST	0.04a	0.00a	0.04a	0.01a	0.32ab	0.45ab
No PRE/oxyfluorfen 0.28 + diuron 2.7 POST	0.01a	0.00a	0.00a	0.10ab	0.89b	0.49ab
Current-year untreated check	0.15a	0.00a	1.13b	0.92c	3.39c	7.64d
Future-year untreated check	0.00a	0.10a	0.04a	0.00a	0.50ab	0.33a
Past-year untreated check	0.21a	0.12a	0.00a	0.68bc	0.37ab	1.58bc
Treatment contrasts						
Current-year untreated check	0.15	0.00	1.13	0.92	3.39	7.64
11-treatment mean	0.04	0.02	0.07	0.11	0.27	0.51
Significance	NS	NS	**	**	***	***
No PRE/oxyfluorfen 0.28 + diuron 2.7 POST	0.01	0.00	0.00	0.10	0.89	0.49
10-treatment mean	0.04	0.02	0.07	0.11	0.22	0.52
Significance	NS	NS	NS	NS	**	NS
Past-year untreated check	0.21	0.12	0.00	0.68	0.37	1.58
9-treatment mean	0.02	0.01	0.08	0.06	0.20	0.43
Significance	NS	NS	NS	***	NS	***
Pendimethalin 2.2 PRE (2-treatment mean)	0.00	0.00	0.14	0.14	0.30	1.06
Pendimethalin 2.2 INC (2-treatment mean)	0.08	0.00	0.00	0.01	0.07	0.39
Significance	NS	NS	NS	NS	NS	†
Pendimethalin 2.2 (PRE and INC)/no POST	0.05	0.00	0.14	0.14	0.27	1.58
Pendimethalin 2.2 (PRE and INC)/4-POST-treatment mean	0.02	0.02	0.02	0.01	0.24	0.24
Significance	NS	NS	NS	NS	NS	***

† Significant *F* tests at the 0.1 probability levels.
** Significant *F* tests at the 0.01 probability level.
*** Significant *F* tests at the 0.001 probability level.
NS, nonsignificant at the 0.1 level.
‡ Means followed by the same letter do not differ at the $P = 0.05$ level within residue management treatments within years.

cover compared with the current-year untreated check except for PRE pendimethalin without any POST follow-up and PRE metolachlor followed by POST oxyfluorfen plus diuron. With bale/flail chop/rake residue removal in 1994, all herbicide treatments reduced roughstalk bluegrass ground cover compared with the current-year untreated check except for PRE pendimethalin without any POST follow-up, PRE metolachlor followed by POST oxyfluorfen plus diuron, and the past-year untreated check. With bale/flail chop/rake in 1995, all herbicide treatments reduced roughstalk bluegrass ground cover compared with the current-year untreated check, although POST-only oxyfluorfen plus diuron was less effective than five of the other treatments. With bale/flail chop/rake in 1996, all herbicide treatments reduced roughstalk bluegrass ground cover compared with the current-year untreated check. However, PRE pendimethalin without any POST follow-up was less effective than all other treatments except for the past-year untreated check, while the past-year untreated check itself was less effective than six of the other treatments.

Residue-Retained

Similar to the situation present in residue-removed management, roughstalk bluegrass plants were too widely scattered at too low a density in the 1992–1993 growing season in residue-retained management to generate meaningful treatment response data. In the final 3 yr, year × PRE treatment, year × POST treatment, and PRE × POST interactions occurred for roughstalk bluegrass ground cover in residue-retained management. Roughstalk bluegrass ground cover increased over time, and was much higher in the absence of INC pendimethalin than in its presence, with the differences being significant in 1995 and 1996, although a similar, but nonsignificant, trend had been present in 1994 (Table 8). Averaged over the last 3 yr, roughstalk bluegrass ground cover was 7.1-fold lower with pendimethalin than without it.

Roughstalk bluegrass ground cover in the current-year no-POST treatment check was 8.5- and 5.1-fold greater than the average of all POST herbicide treatments in 1995 and 1996 (Table 8). Roughstalk bluegrass ground cover in the past-year no-POST treatment check was 4.9 and 6.2-fold greater than the nine-treatment mean in 1994 and 1996 (Table 7). POST oxyfluorfen plus diuron did not differ in roughstalk bluegrass ground cover from the five EP followed by LP sequential application treatments in any year. Averaged over the last 3 yr, both the current-year and the past-year no-POST treatment checks contained much more roughstalk bluegrass than the other POST treatments when no PRE herbicide was applied. When INC-pendimethalin was applied, however, roughstalk bluegrass density was low even without POST treatment.

Impact of Weeds on Tall Fescue Seed Yield

Past-year untreated checks were generally the lowest yielding treatments under both residue-removed and

Table 8. Ground cover of roughstalk bluegrass among herbicide treatments with residue-retained management from 1994 through 1996.

Main effects	Main effects within years			Interaction averages over years	
	1994	1995	1996	No PRE herbicide	Pendimethalin INC
	0% ground cover				
PRE herbicide treatment (kg a.i. ha^{-1})					
No PRE herbicide	0.39a†	0.85b	1.11b	0.76y	–
Pendimethalin 2.2 INC	0.06a	0.08a	0.18a	–	0.11x
POST herbicide treatment (kg a.i. ha^{-1})					
Oxyfluorfen 0.28 + metolachlor 2.2 EP/diuron 2.7 LP	0.18a	0.40a	0.21ab	0.50b	0.06a
Oxyfluorfen 0.28 + metribuzin 0.63 EP/diuron 1.8 LP	0.18a	0.25a	0.53b	0.49b	0.16a
Oxyfluorfen 0.28 + terbacil 1.1 EP/diuron 1.8 LP	0.11a	0.16a	0.34ab	0.40ab	0.03a
Oxyfluorfen 0.28 EP/diuron 2.7 LP	0.17a	0.27a	0.47ab	0.48b	0.14a
Oxyfluorfen 0.42 + diuron 0.9 EP/diuron 1.8 LP	0.15a	0.05a	0.02a	0.10a	0.04a
Current-year no-POST check	0.30ab	2.20b	2.18c	3.46c	0.25a
Past-year no-POST check	0.68b	0.46a	1.75c	2.27c	0.09a
Oxyfluorfen 0.42 + diuron 2.7 POST	0.05a	0.26a	0.19ab	0.23ab	0.10a
	Treatment contrasts				
Current-year no-POST treatment	0.30	2.20	2.18	3.46	0.25
7-POST mean	0.20	0.26	0.43	0.54	0.09
Significance	NS	***	***	***	NS
Past-year no-POST treatment	0.68	0.46	1.75	2.27	0.09
6-POST mean	0.14	0.23	0.28	0.36	0.09
Significance	***	NS	***	***	NS
Oxyfluorfen 0.42 + diuron 2.7 POST	0.05	0.26	0.19	0.23	0.10
EP + LP 5-herbicide mean	0.16	0.22	0.30	0.38	0.08
Significance	NS	NS	NS	NS	NS

*** Significant F test at the 0.001 probability level.
NS, nonsignificant at the 0.1 level.
† Means followed by the same letter do not differ at the $P = 0.05$ level within PRE herbicide main plot or POST herbicide subplot treatments.

residue-retained conditions, while yields of current-year untreated checks were variable (Tables 5 and 6). In cases where yields of current-year untreated checks were reduced compared with averages for herbicide treatments (e.g., 1993 residue-retained and 1996 residue-removed tests), there were relatively large differences in volunteer tall fescue seedling ground cover between untreated checks and herbicide-treated plots (Tables 3 and 4). In the past-year untreated checks, both roughstalk bluegrass and year-old volunteer tall fescue plants were present to compete with the crop. Analyses of covariance were used to evaluate the impact of volunteer tall fescue seedlings, volunteer tall fescue year-old plants, and roughstalk bluegrass on tall fescue seed yield. Coefficients relating variation in seed yield to variation in volunteer tall fescue seedling ground cover ranged from a loss of 7.3 kg ha^{-1} seed for each 1% increase in ground cover in 1994 with residue-retained to a gain of 8.7 kg ha^{-1} seed in 1995 with residue-removed management. This apparent increase in yield with increasing volunteer tall fescue seedling ground cover probably indicated that injury from herbicide treatments reduced crop yield in 1995. Coefficients relating tall fescue seed yield to ground cover of year-old volunteer tall fescue plants ranged from a loss of 16.7 kg ha^{-1} seed for each 1% increase in ground cover in 1994 to a loss of only 0.9 kg ha^{-1} seed in 1996 under residue-retained conditions. Coefficients relating tall fescue seed yield to roughstalk bluegrass ground cover ranged from a loss of 24.1 kg ha^{-1} seed for each 1% increase in ground cover in 1994 to a loss of 5.0 kg ha^{-1} seed in 1995 under residue-removed conditions.

Converting seed yields from kg ha^{-1} to percentage of yearly averages allowed analyses of covariance to be conducted on data pooled over years and/or residue management methods. Pooling residue-removed and residue-retained tests, yield impact coefficients were −0.05, −0.61, +0.48, and −0.63% yield change for each 1% increase in volunteer tall fescue seedling ground cover in 1993, 1994, 1995, and 1996, respectively. Similarly, yield impact coefficients were −0.46, −0.49, and −0.32% yield change for each 1% increase in year-old tall fescue ground cover in 1994, 1995, and 1996, respectively. Yield impact coefficients were −1.48, −0.87, and −0.86% yield change for each 1% increase in roughstalk bluegrass ground cover in 1994, 1995, and 1996, respectively. In analyses pooled over years and residue management methods, yield loss coefficients were 0.21, 0.68, and 0.82% yield reduction for each 1% increase in ground cover by volunteer tall fescue seedlings, volunteer tall fescue year-old plants, and roughstalk bluegrass, respectively. An important difference between these results and those obtained in concurrent tests in perennial ryegrass was the impact of year-old volunteer crop plants on seed yield (Mueller-Warrant and Rosato, 2002a and 2002b). In perennial ryegrass, volunteer crop plants were reproductively mature by their second growing season, and their presence increased total seed yield. In contrast, year-old volunteer tall fescue remained immature, and competed with the crop. Roughstalk bluegrass was an even more competitive weed, and percentage decreases in tall fescue seed yield were nearly identical to increases in roughstalk bluegrass ground cover. Annual bluegrass also occurred in many of the plots containing roughstalk bluegrass, but at far lower density. Variation in annual bluegrass density was too small to determine yield loss coefficients for that weed by the analysis of covariance technique.

Residue-Retained vs. Residue-Removed Management

Three methods existed for directly comparing residue-retained and residue-removed management. The most rigorous method was to select just those herbicide treatments that were identical in the residue-retained and residue-removed tests, and then perform *t* tests among management systems for each herbicide treatment. A less rigorous method began with selection of a somewhat larger group of herbicide treatments, those that included the same chemicals but with possible minor differences in application timing or total rate, followed by performing *t* tests among residue management systems. A third method involved graphing tall fescue seed yield vs. ground cover of roughstalk bluegrass, seedling volunteer tall fescue, or year-old volunteer tall fescue, and then testing separate regressions for each residue management system versus pooled regressions with common slopes and common or differing intercepts.

In comparisons involving identical herbicide treatments, seed yields of the no-herbicide checks were higher for vacuum sweep than residue-retained in all 4 yr, and yields of the untreated checks were higher for bale/flail chop/rake than residue-retained in the first 3 yr. Seed yields of INC pendimethalin without any POST follow-up treatment were higher for vacuum sweep than residue-retained the first and last years and were higher for bale/flail chop/rake than residue-retained the first year. In comparisons involving herbicide treatments that were similar but not necessarily identical, vacuum sweep out-yielded residue-retained in 14 out of 23 cases, while bale/flail chop/rake out-yielded residue-retained in nine out of 23 cases.

Regression analysis of yield vs. combined weed pressure (sum of the products of the pooled yield loss coefficients for each weed and the ground cover of volunteer seedling tall fescue, year-old tall fescue, and roughstalk bluegrass) helped to further characterize differences among the residue management practices. Regressions of yield vs. combined weed pressure differed in their intercepts but not their slopes, with vacuum sweep yielding 9% more than bale/flail chop/rake at common weed pressure, while bale/flail chop/rake in turn yielded 12% more than residue-retained at common weed pressure (Fig. 2). Although regressions were significant at the $P = 0.001$ level, the relatively low R-square value of 0.12 suggests that other factors also influenced tall fescue seed yield. Other factors probably affecting yield but not included in the regression model were (i) herbicide damage to the crop, (ii) variability in soil type, drainage, and moisture across the plots, (iii) nonuniformity in crop stands, and (iv) sporadic mechanical problems during grass seed harvest. The dispersion in seed yields around the regression lines suggests that herbicide treatments may exist that could overcome the differences between residue-retained and residue-removed conditions. Among the treatments we tested, residue-retained plots needed to receive INC pendimethalin followed by EP oxyfluorfen plus metolachlor and LP diuron to most closely match yields seen for many herbicide treatments in bale/flail chop/rake residue-removed plots. Weed control and seed

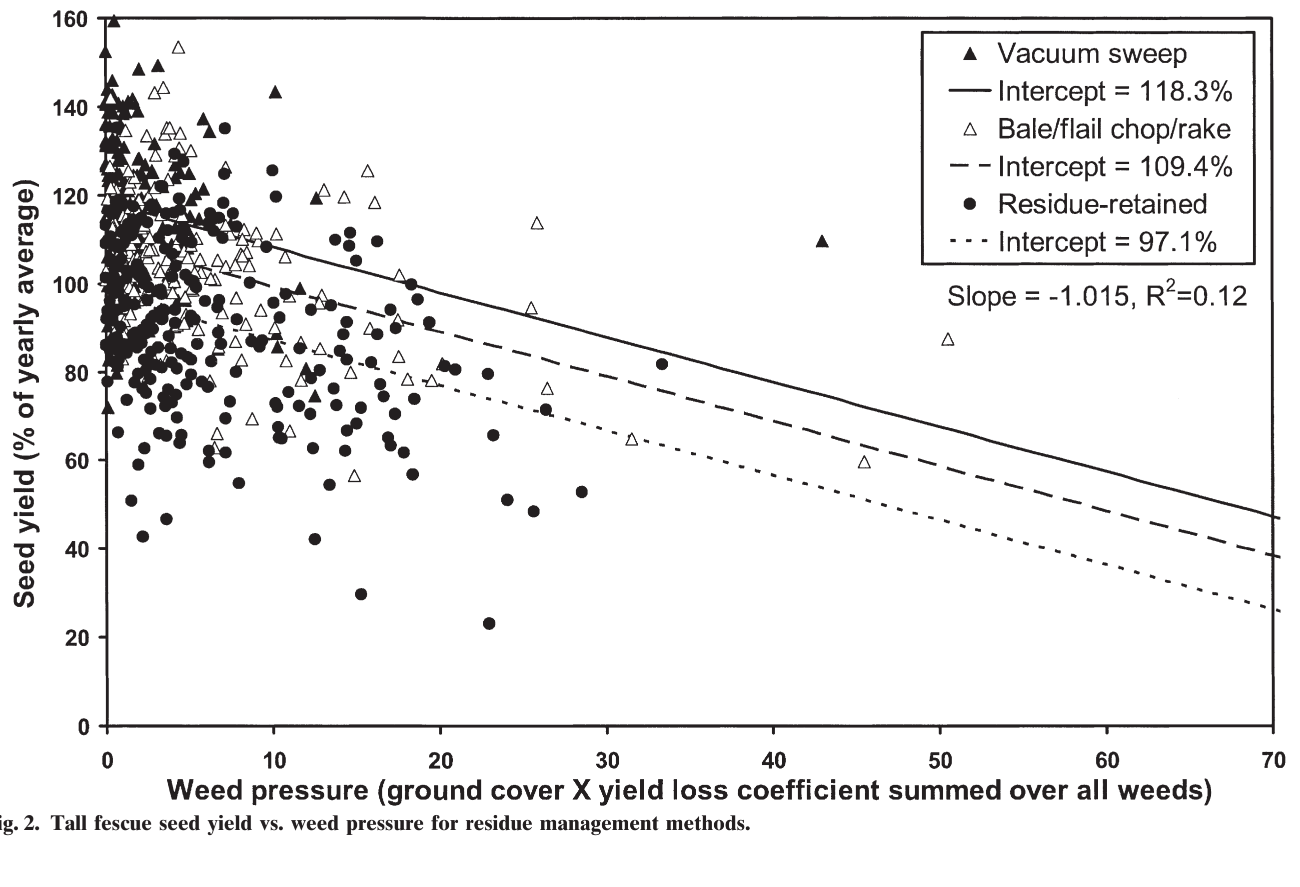

Fig. 2. Tall fescue seed yield vs. weed pressure for residue management methods.

yield benefits of vacuum sweep, although clearly present, have not proved large enough to overcome grower concerns about the slow operating speed of the equipment and the high cost of the treatment.

SUMMARY

Weeds could be adequately controlled throughout the normal 6-yr life of a tall fescue stand in western Oregon by vacuum sweep, bale/flail chop/rake, or residue-retained management if suitable herbicide treatments were applied. Suitable herbicide treatments generally included both PRE and POST components. Pendimethalin, metolachlor, and oxyfluorfen all functioned as satisfactory PRE herbicides if they were applied immediately before, or during, the onset of rains that germinated volunteer tall fescue seed laying on the soil surface. Performance of pendimethalin was improved by shallow incorporation in bale/flail chop/rake and residue-retained systems. POST follow-up treatments usually improved control over that from just the PRE component. Uncontrolled volunteer seedlings usually reduced seed yield during their first year of growth but were far more competitive during their second year. Proliferation of highly competitive weeds such as roughstalk bluegrass posed serious problems for tall fescue seed production, and such weeds must be controlled if stands are to remain productive. Western Oregon tall fescue seed growers need to risk some yield loss in the current year of production from herbicide injury to avoid greater losses in future years from weeds such as roughstalk bluegrass. Yields with residue-retained management were often lower than with residue-removed management, and varying weed pressure between the systems explained only part of the differences in yield.

Extension of our results to other locations, varieties, years, residue management practices, and economic conditions would require a variety of assumptions. Because this study was conducted in Linn County, the heart of Oregon's traditional grass production hectarage, it closely matches the soil types and climate present in a majority of western Oregon tall fescue seed fields. Similar benefits from controlling grassy weeds would almost certainly accrue in other tall fescue stands in western Oregon. Likewise, there would be similar risks of crop damage from these particular herbicide treatments. However, variation in weed species abundance among tall fescue seed fields in western Oregon could substantially change the need for, and value of, specific herbicide treatments. Extrapolating results to other production systems such as irrigated sands of the Columbia River Basin or rainfed, opportunity-seed-harvest pastures in Missouri would require careful consideration of many factors, including (i) higher seedling mortality and greater crop injury during harsher winter weather, (ii) shorter stand rotations because of economic attractiveness of alternative crops, and (iii) lessened concern over weed seed contamination in uncertified seed of common forage types.

Even in western Oregon, yearly variation in weather patterns can greatly alter both the feasibility and value of applying specific herbicide and residue management treatments. Sporadically heavy rainfall in August can germinate large numbers of weed seeds and eliminate most of the benefits of late September applications of PRE herbicides like pendimethalin. Occasional extremely low winter temperatures can severely injure both crops and weeds, causing growers to regret their decision to apply some POST herbicide treatments. Timeliness of PRE applications can be adversely impacted by equipment malfunctions, higher priority labor needs, physical availability of herbicides, and excessive wind speeds. Because added benefits of incorporating pendimethalin were generally smaller than the value of simply getting it applied in a timely manner, growers should opt for treating as much of their hectarage under truly PRE conditions as possible and only attempt to incorporate pendimethalin when that can be done without delaying other time-critical farming operations. Because performance of pendimethalin, metolachlor, and several newer herbicides varies with both duration of exposure before rain and size of weed seedlings when treated, growers should shift among these herbicides as the season progresses and conditions change. INC pendimethalin is best suited to applications made a month or more ahead of the anticipated onset of fall rains, pendimethalin (PRE or INC) is best in the final month before rain, metolachlor is best in the first week after rains arrive, while oxyfluorfen tank-mixes are best once weed seedlings have emerged. Sequential PRE and POST applications of herbicide treatments improve weed control efficacy and reduce the risk of crop injury over tank-mixes of multiple products on a single application date. Another advantage of the sequential application approach is the availability of the option of omitting one or more later applications in cases where weeds are already well controlled by previously applied herbicides, where severe winter weather has arrived before the final treatments are applied, or when the crop is in its final year of production and volunteer crop seedlings are the only major weeds present.

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